

# A Physically Based Compact Model for Eigenenergy in In rich $\text{In}_{1-x}\text{Ga}_x\text{As}$ MOSFETs Using Modified Airy Function Approximation

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**Abstract**—We propose a compact model for calculating the quantized energy levels in  $\text{InGaAs}$  MOSFETs with  $\text{Al}_2\text{O}_3$  gate dielectric. The model is based on the modified Airy function approximation, originally developed for Si nano-MOSFETs. The parameters of the model are extracted from numerical results calculated by self-consistent solution of one-dimensional Schrödinger and Poisson equation including the effect of wave function penetration into the gate dielectric. It is found that the compact model parameters are not sensitive to the variations in the In content in the channel layer and to the substrate doping density. Therefore, constant values of the parameters are proposed for both electrons and holes.

**Index Terms**— $\text{InGaAs}$  MOSFET, quantum mechanical effect, wave function penetration, compact model.

## I. INTRODUCTION

Si MOSFETs are nearly reaching its fundamental limits due to continuous scaling according to Moore's Law. III-V MOSFETs are being considered as potential replacements of Si MOSFETs for 22 nm node and beyond [1]. This type of MOSFETs have been successfully fabricated recently [2]. Among different III-V MOSFETs,  $\text{InGaAs}$  channel MOSFETs are found to be attractive due to improved performances [3].

With the development of III-V MOSFETs, compact models of these devices are necessary to predict the performance of integrated circuits containing such transistors. Electron (hole) energies become quantized under a gate bias due to high surface electric field in these state-of-the-art nanoscale transistors. This quantum mechanical effect (QME) needs to be incorporated accurately in compact models [4]. However, simple analytical models for QME based on Airy function approximation or variational principle are not accurate [5]. Self-consistent models can take QME into account accurately but these are not suitable for compact models due to time consuming numerical calculations. Li *et al.* have introduced a semi-empirical relationship for QME in Si nano-MOSFETs based on the modified Airy function approximation. This model proposes a relationship between the quantized electron (hole) energy states in the channel and the oxide electric field. The modified Airy function approximation, involves two parameters for electrons (holes) [6]. Since this model considers the deviation of the potential profile from linearity and the penetration of electron (hole) wavefunction into gate

dielectric, it is accurate. At the same time the model is also computationally efficient.

In this paper, we have modified the model of Li *et al.* to make it applicable to  $\text{InGaAs}$  MOSFETs with high In content. Schematic diagram of the device structure considered in this paper is shown in Fig. 1. The two parameters of the model are extracted by comparing with the results of the self-consistent solution of one-dimensional Schrödinger and Poisson equations.

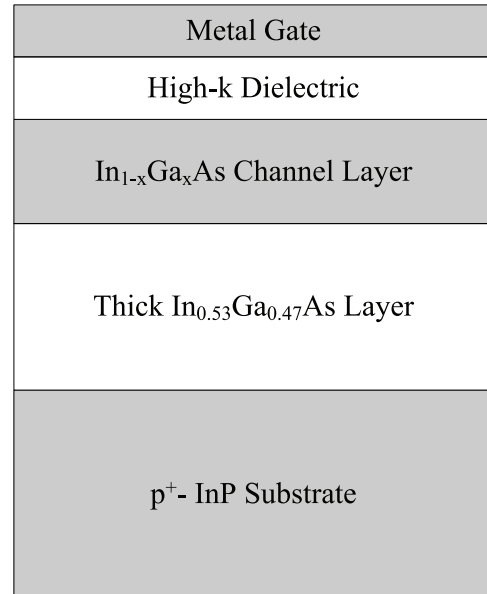


Fig. 1. Geometry of the device considered in this paper.

## II. QM MODEL

When a high bias voltage is applied to the gate of a MOSFET, a potential well is formed in the channel near the surface where the electron (hole) energies become quantized. According to the Airy function approximation, if this well could be approximated as an infinite triangular well, the quasi bound energy states are proportional to  $(F_{ox})^{2/3}$  [5], where  $F_{ox}$  is the oxide electric field. However, if the variation in the potential function from the triangular well is taken into account and the penetration of electron (hole) wavefunction into the

gate dielectric is considered, the two-third power law is less accurate for modern state-of-the-art nanoscale MOSFETs. It has been shown in [6], that a power law relationship still holds for these cases although the exponent is different from 2/3.

From [6], the energy of the lowest quasi bound state  $E_1$ , which is measured from the respective band edge, is expressed as,

$$E_1 \cong \pm \zeta \left( \frac{|F_{ox}| \text{cm}}{\text{MV}} \right)^\lambda \quad (1)$$

Here, for Si MOSFETs,  $\zeta = 77$  meV and  $\lambda = 0.61$  for electrons and  $\zeta = 88$  meV and  $\lambda = 0.64$  for holes.

In this paper, we have extracted the two parameters  $\zeta$  and  $\lambda$  for both electrons and holes in  $\text{Al}_2\text{O}_3/\text{In}_x\text{Ga}_{1-x}\text{As}$  MOSFETs. Quantized electron (hole) states of a MOS inversion/accumulation layer are calculated via self-consistent solution of one-dimensional (1-D) Schrödinger and Poisson equations within the effective mass approximation [7] and wave function penetration effect is taken into account by considering open boundary condition at the semiconductor dielectric interface [8]. The effect of strain and the variation of the material compositions on the conduction and valence band edges, electron affinities and effective masses in each hetero layer of the MOS structure is taken into account using the relationships given in [9].

### III. RESULTS AND DISCUSSION

Extracted values of  $\zeta$  and  $\lambda$  are independent of gate oxide thickness and channel layer thickness as long as the mobile charges are confined within the channel layer. We have performed self-consistent simulation for a channel layer of 20 nm and gate oxide of 10 nm. In fraction in the channel region is taken to be 0.53, 0.65 and 0.75, respectively. All the simulations have been performed for three different doping densities:  $1 \times 10^{17}$ ,  $5 \times 10^{17}$  and  $1 \times 10^{18}$   $\text{cm}^{-3}$ . This set of device parameters encompasses the practical values of interest for the III-V devices for which experimental results are reported [10]. The results presented here are applicable for any high-k gate dielectric with barrier height  $\Delta E_c$  or  $\Delta E_v$  between semiconductor and gate dielectric interface comparable with those of  $\text{Al}_2\text{O}_3$ , since  $\lambda$  is actually a function of the barrier height [11].

Figs. 2, 3 and 4 present  $E_1$  for electrons and corresponding inversion sheet carrier density calculated from the self-consistent numerical simulation with respect to the oxide field for three different acceptor doping densities. Negligible change in both eigenenergy and sheet carrier density is observed with the variation in In fraction.  $E_1$  can be fitted well with Eq. (1). The parameters  $\zeta$  and  $\lambda$  are extracted from Figs. 2, 3 and 4 for different In fractions and doping densities. The extracted parameters are presented in Fig. 5 with respect to the variation in In fraction. It is observed that with the increasing doping density,  $\zeta$  is increasing but  $\lambda$  is decreasing. However, the changes observed in the parameters are small enough to propose a single parameter set for electrons irrespective of the doping density or In fraction. Hence, we propose  $\lambda = 0.52$  and  $\zeta = 211$  meV for electrons in In rich III-V MOSFETs. These two values are chosen so that the

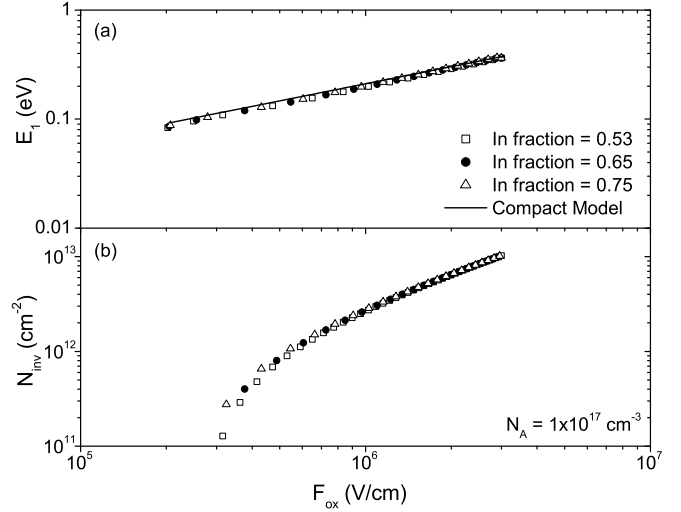


Fig. 2. (a) Subband minima and (b) inversion sheet carrier density as a function of oxide field for different In fraction for a doping density of  $1 \times 10^{17}$   $\text{cm}^{-3}$ .

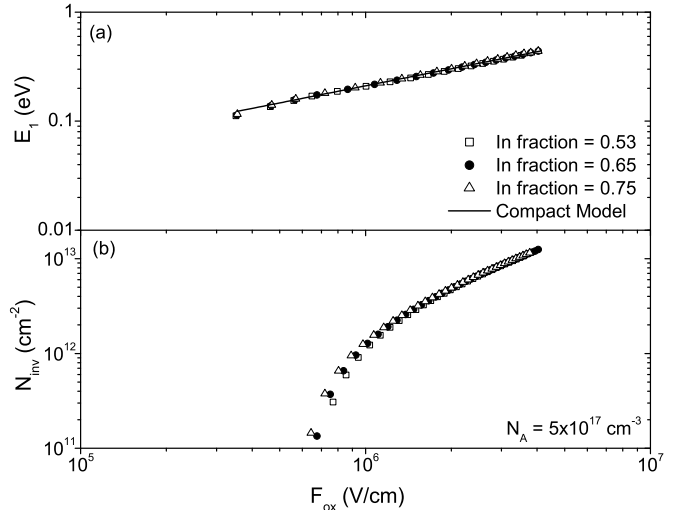


Fig. 3. (a) Subband minima and (b) inversion sheet carrier density as a function of oxide field for different In fraction for a doping density of  $5 \times 10^{17}$   $\text{cm}^{-3}$ .

overall percentage of error in calculating  $E_1$  is minimized. To examine the justification of our proposed parameters, we present a comparative analysis of  $E_1$  calculated from both self-consistent calculation and the proposed compact model in Table I. In this table  $E_1$  at a sheet carrier density of  $10^{13}$   $\text{cm}^{-2}$  is shown along with the corresponding percentage error. From this table, it has been observed that for electrons the worst case error in calculating  $E_1$  is less than 3% for all doping densities and In fractions.

To observe the validity of the proposed model, we have plotted  $E_1$  calculated from Eq. (1) along with the self-consistently calculated eigenenergies in Figs. 2, 3 and 4 in inversion bias region. Excellent agreement between the compact model and the self-consistent results are observed for all doping densities and In fractions. The sheet carrier density curve reveals that for all doping densities and In fractions, the proposed model

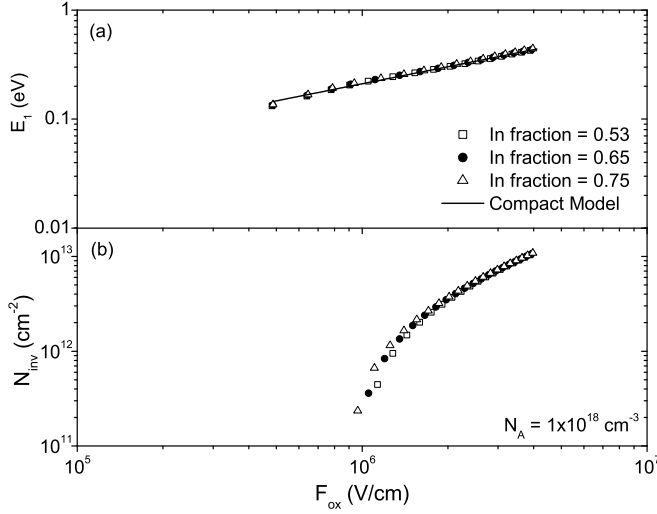


Fig. 4. (a) Subband minima and (b) inversion sheet carrier density as a function of oxide field for different In fraction for a doping density of  $1 \times 10^{18} \text{ cm}^{-3}$ .

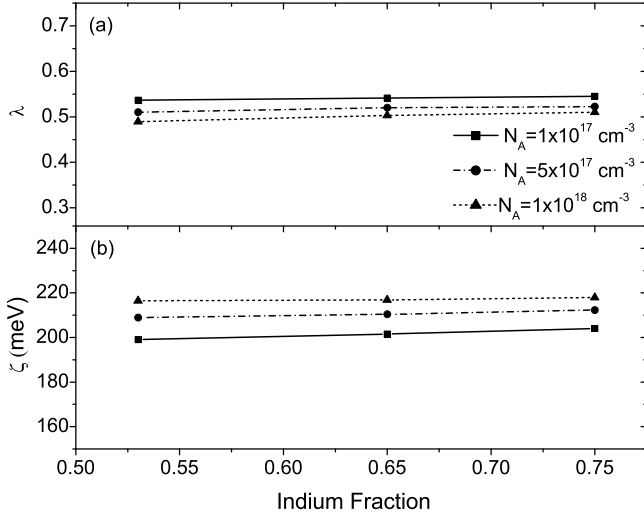


Fig. 5. Variation of (a)  $\lambda$  and (b)  $\zeta$  with respect to the fraction of Indium in the channel layer for three different doping densities.

fits well in the bias region where the sheet carrier density is  $10^{11} \text{ cm}^{-2}$  or higher.

We have simulated the same set of devices with n-type substrate in order to formulate the hole energy compact model. In case of holes, there are three bands of which heavy-hole and light-hole bands are degenerate in unstrained condition. Except for tensile strained channel, the lowest hole energy level is heavy-hole type. So heavy-hole band is of primary interest. Figs. 6, 7 and 8 present  $E_1$  with respect to oxide field for different In fractions. In each figure, corresponding hole inversion sheet carrier density is also shown. Like electrons, both heavy-hole energy and sheet carrier density show negligible variation with In fraction. The eigenenergy curve is fitted with Eq. (1) and the extracted parameters ( $\zeta$ ,  $\lambda$ ) are shown in Fig. 9. Here, the variations of  $\zeta$  and  $\lambda$  with respect to doping density and In fraction are similar to

TABLE I  
COMPARISON OF ELECTRON SUBBAND MINIMA CALCULATED FROM THE PROPOSED MODEL WITH THAT OBTAINED FROM THE SELF-CONSISTENT CALCULATION

Indium Fraction	$N_A$ ( $\text{cm}^{-3}$ )	Subband Minima, $E_1$ (eV)		% Error
		Simulation	Proposed model	
0.53	$1 \times 10^{17}$	0.3617	0.3712	2.63
	$5 \times 10^{17}$	0.3948	0.3996	1.22
	$1 \times 10^{18}$	0.4213	0.4219	0.14
0.65	$1 \times 10^{17}$	0.3664	0.3706	1.15
	$5 \times 10^{17}$	0.3996	0.3988	-0.20
	$1 \times 10^{18}$	0.4262	0.4209	-1.24
0.75	$1 \times 10^{17}$	0.3700	0.3688	-0.32
	$5 \times 10^{17}$	0.4035	0.4002	-0.82
	$1 \times 10^{18}$	0.4302	0.4189	-2.63

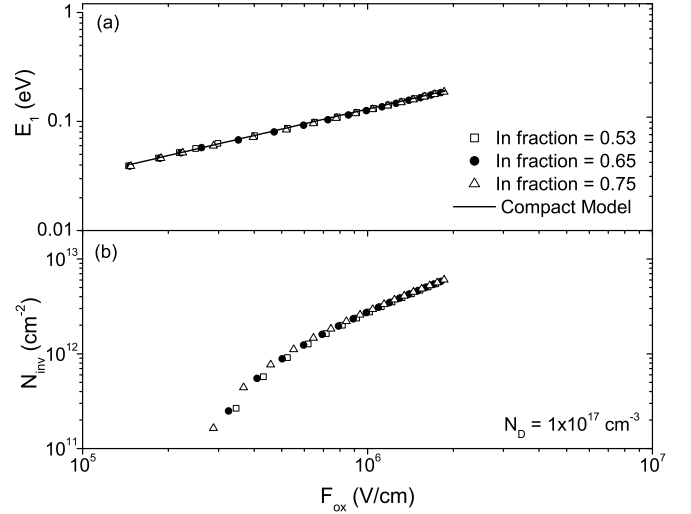


Fig. 6. (a) Heavy-hole energy and (b) inversion sheet carrier density as a function of oxide field for different In fraction for a doping density of  $1 \times 10^{17} \text{ cm}^{-3}$ .

those of electrons. However, these variations are smaller for holes compared to electrons. Again, we propose a constant parameter set for holes, so that the overall error in energy calculation is minimized. Here,  $\lambda = 0.61$  and  $\zeta = 130 \text{ meV}$ .

Next, we compare  $E_1$  obtained from the model using the proposed parameters with that of the self-consistently calculated value. In Table II, the comparison is shown for a sheet carrier density of  $5 \times 10^{12} \text{ cm}^{-2}$ . From the table, it is observed that in the worst case the error is less than 2.5%.  $E_1$  for different In fractions obtained from the proposed compact model are shown in Figs. 6, 7 and 8 along with the self-consistently calculated energies. Excellent match is observed for the range of inversion bias starting from the sheet carrier density of  $10^{11} \text{ cm}^{-2}$ .  $\zeta$  and  $\lambda$  proposed for electrons (holes) are also valid for estimating lowest eigenenergies in the accumulation bias region [6].

#### IV. CONCLUSION

A physically based compact model for QME in In rich channel enhancement type InGaAs MOSFETs is presented. The key parameters in the model,  $\zeta$  and  $\lambda$  are proposed both for electrons and holes. It has been found that In fraction and doping density has an insignificant effect on the parameters.

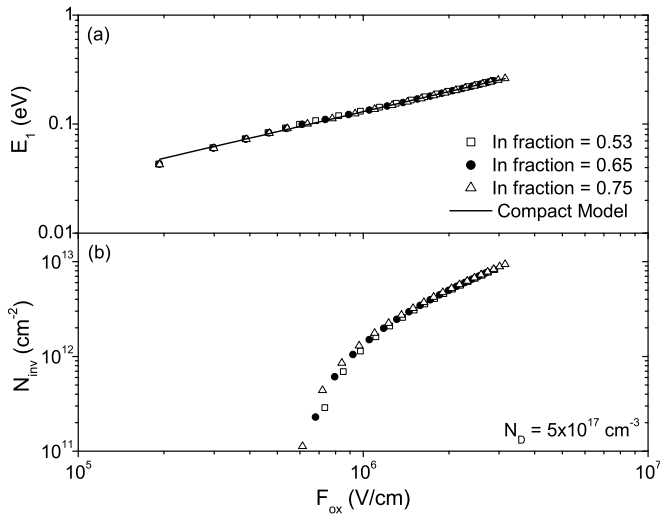


Fig. 7. (a) Heavy-hole energy and (b) inversion sheet carrier density as a function of oxide field for different In fraction for a doping density of  $5 \times 10^{17} \text{ cm}^{-3}$ .

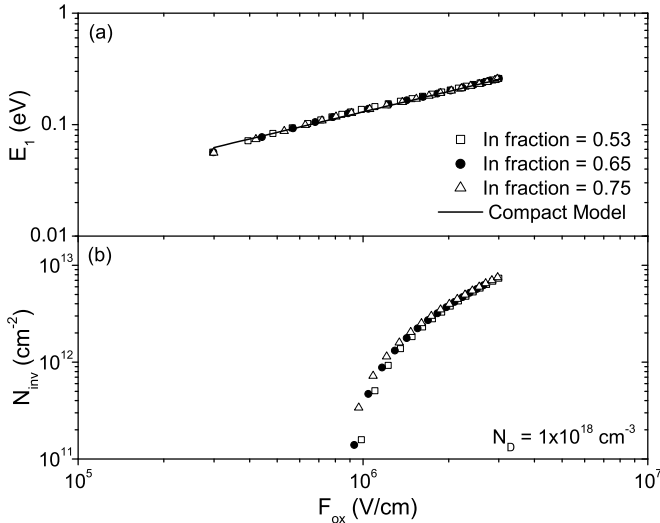


Fig. 8. (a) Heavy-hole energy and (b) inversion sheet carrier density as a function of oxide field for different In fraction for a doping density of  $1 \times 10^{18} \text{ cm}^{-3}$ .

Hence constant values are proposed for both the parameters. The model shows excellent match with the eigenenergies obtained from self-consistent numerical calculation.

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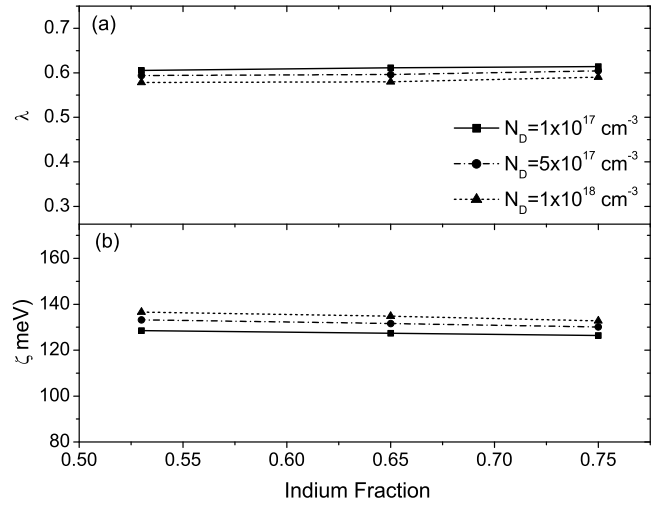


Fig. 9. Variation of (a) $\lambda$  and (b) $\zeta$  with respect to the fraction of Indium in the channel layer for three different doping densities.

TABLE II  
COMPARISON OF THE LOWEST HEAVY-HOLE ENERGY CALCULATED FROM THE PROPOSED MODEL WITH THAT OBTAINED FROM THE SELF-CONSISTENT CALCULATION

Indium Fraction	$N_D$ ( $\text{cm}^{-3}$ )	Subband Minima, $E_1$ (eV)		%
		Simulation	Proposed model	
0.53	$1 \times 10^{17}$	0.1741	0.1752	0.63
	$5 \times 10^{17}$	0.2041	0.2019	-1.08
	$1 \times 10^{18}$	0.2249	0.2201	-2.13
0.65	$1 \times 10^{17}$	0.1708	0.1733	1.46
	$5 \times 10^{17}$	0.2004	0.2001	-0.15
	$1 \times 10^{18}$	0.2209	0.2182	-1.22
0.75	$1 \times 10^{17}$	0.1685	0.1721	2.14
	$5 \times 10^{17}$	0.1978	0.1989	0.56
	$1 \times 10^{18}$	0.2180	0.2171	-0.41

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